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Late Miocene ostracodes from the Kubota Formation, Higashi-Tanagura Group, Northeast Japan, and their implications for bottom environments

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Abstract. **Sixty-seven ostracode species including those in open nomenclature are identified in thirty-six samples from the upper Miocene Kubota Formation, Higashi-Tanagura Group, distributed in Fukushima Prefecture, northeastern Japan. The lower part of the Kubota Formation yields *Spinileberis* sp. dominantly. In the middle to upper part of the formation, dominant species are *Schizocythere kishinouyei* (Kajiyama), *Kotoracythere abnorma* Ishizaki, *Hanaiborchella triangularis* (Hanai), *Cytheropteron miurense* Hanai, *Paracytheridea neolongicaudata* Ishizaki and *Finmarchinella japonica* (Ishizaki). Most of these species live off southwestern Japan under a subtropical to warm marine climate regime, but cryophilic and circumpolar species also occur sparsely in the middle to upper part. The ostracode assemblages indicate that the lower and the middle to upper parts of the Kubota Formation were deposited in an enclosed inner bay influenced by warm water and a warm shallow sea, respectively. Principal component analysis reveals that the influence of open sea water became strong in the upward sequence of the middle part. Analyses of ostracode faunas indicate that the Shiobara fauna from the Kubota Formation flourished in warm-water conditions.**

Key words: **Kubota Formation, Late Miocene, Ostracoda, Shiobara fauna**

Introduction

The Kubota Formation is known as one of the units containing the Shiobara fauna (Iwasaki, 1970), which flourished in Northeast Japan during the middle to late Miocene.

Chinzei and Iwasaki (1967) and Iwasaki (1970) considered that the Akasaka and Kubota Formations of the Higashi-Tanagura Group were deposited contemporaneously in an inner bay. Furthermore, these authors reconstructed a Higashi-Tanagura Bay on the basis of the lithology and geometry of the basin, discussing the paleoecology of the molluscan assemblages. In their discussion, Chinzei and Iwasaki (1967) compared the molluscan assemblages in the eastern Tanagura area with ones belonging to the Kadonosawa and Tatsunokuchi faunas, and recognized parallel communities. Iwasaki (1970) made a comparison with the molluscan assemblages in the eastern Tanagura, Shiobara, and Takasaki areas, where nearly contemporaneous deposits are distributed. Consequently, he recognized parallel communities between them and defined the Shiobara-type fauna (Shiobara fauna).

The Shiobara fauna was defined as a cold-water fauna which lived in inner bays or coastal areas (e.g. Chinzei, 1963; Chinzei and Iwasaki, 1967; Chinzei, 1986). Recently some workers, however, pointed out that the fauna flourished in warm- to mild-temperate realms rather than cold-temperate ones, or contained warm-water species as well as cold-water ones (e.g. Ogasawara *et al.*, 1985; Ogasawara, 1994; Ozawa *et al.*, 1996). Thus, the Shiobara fauna has been studied by many workers paleoecologically.

Many studies on the Miocene paleoenvironments have been made using molluscan fossils. For example, Chinzei (1986) and Ogasawara (1994) summarized the molluscan faunas of the late Cenozoic of Japan in the light of paleoclimates. Chinzei (1986) stated that Northeast Japan was influenced by cold water during the middle to late Miocene, since he regarded the Shiobara fauna as a cold-water fauna. On the other hand, Ogasawara (1994) thought

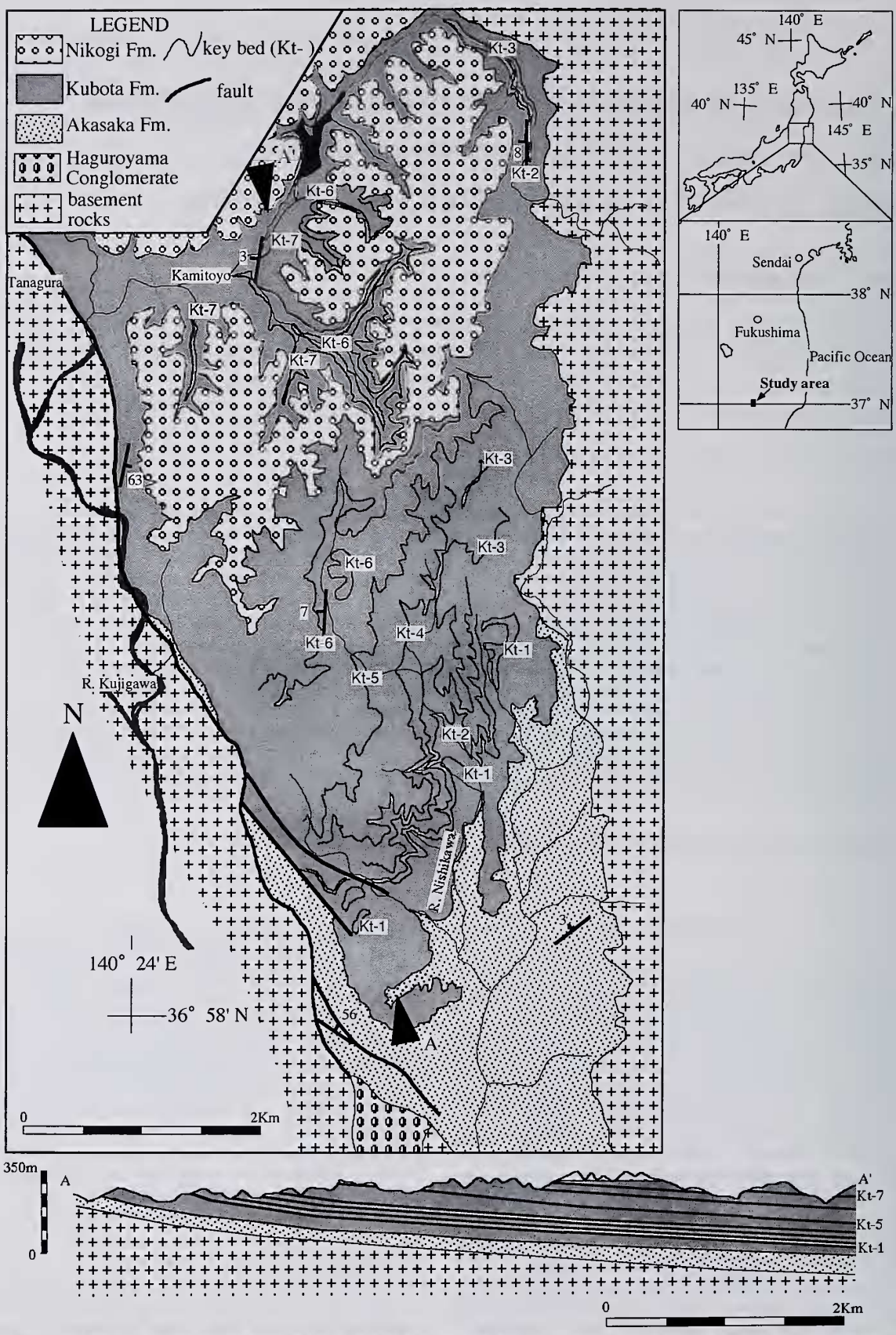
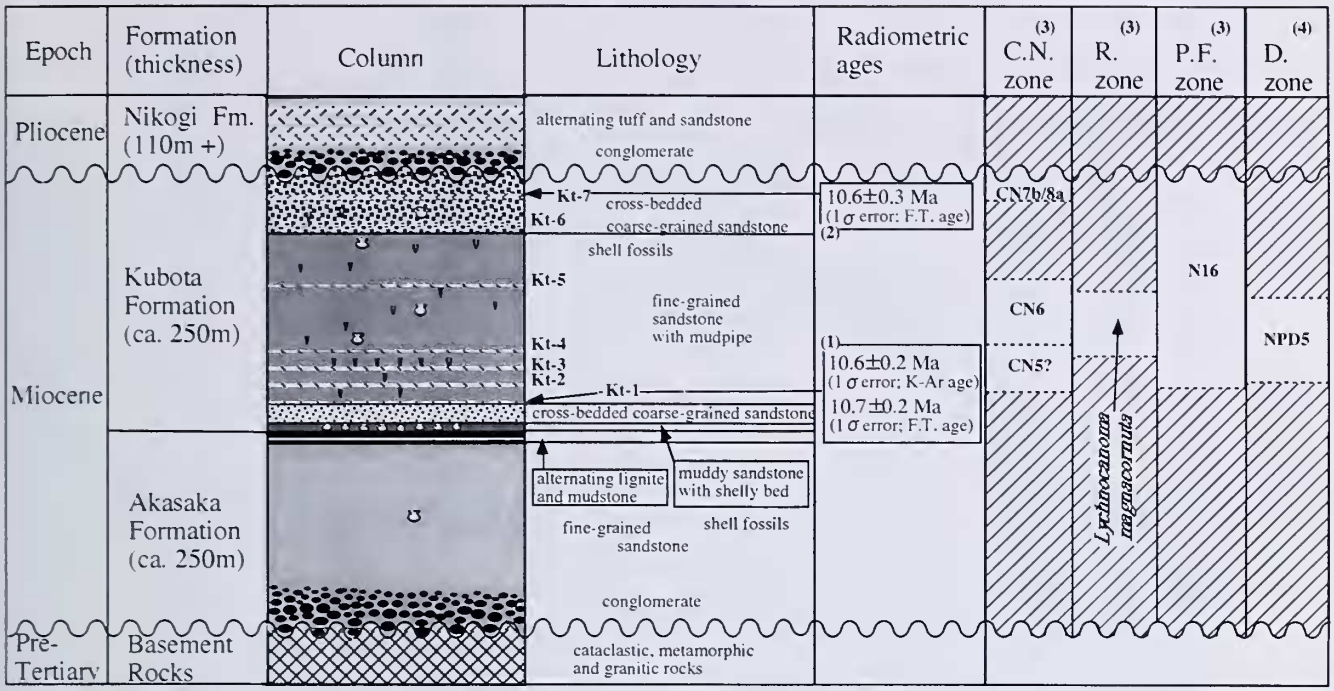


Figure 1. Geological sketch map and geological cross section of the eastern Tanagura area. Partly modified after Shimamoto *et al.* (1998) for the geological map.



(1) Takahashi *et al.* (2001) (2) Takahashi *et al.* (in press) (3) Shimamoto *et al.* (1998) (4) Yanagisawa *et al.* (2000)

Figure 2. Diagram showing the Neogene sequence in the eastern Tanagura area and biostratigraphy and radiometric ages of tuff layers of the Kubota Formation. Compiled after Shimamoto *et al.* (1998) and Yanagisawa *et al.* (2000) for biostratigraphy and Takahashi *et al.* (2001) and Takahashi *et al.* (in press) for radiometric ages.

that marine climates in Northeast Japan were warm- to mild-temperate during the middle to late Miocene, based on the modern distribution of molluscan genera and the marine zoogeographic divisions of Nishimura (1981). Paleoclimates suggested by molluscan fossils have been based on their biogeography and phylogeny. However, only a few studies have been made on other fossil groups from deposits yielding the Shiobara fauna.

To approach the problems mentioned above, we quantitatively examined ostracodes from the upper Miocene Kubota Formation of the Higashi-Tanagura Group.

Geological setting

The eastern Tanagura area lies about 70 km south of Fukushima City, Fukushima Prefecture, northeastern Japan (Figure 1).

The geology of the eastern Tanagura area has been studied by many workers (e.g., Chinzei and Iwasaki, 1967; Iwasaki, 1970; Otsuki, 1975; Shimamoto *et al.*, 1998). The Miocene distributed in the eastern Tanagura area comprises two formations: the Akasaka and Kubota Formations (Figures 1, 2). The Kubota Formation overlies conformably the Akasaka Formation and is overlain unconformably by the Pliocene Nikogi Formation. On the basis of lithology, the Kubota Formation is divided into three parts (Shimamoto *et al.*, 1998): the lower part is composed of muddy fine-grained sandstone, yielding abundant molluscan fossils, and medium- to coarse-grained sandstone; the middle part muddy fine-grained sandstone with mud-pipes and tuffaceous sandstone; the upper part cross-bedded coarse-grained sandstone. Many felsic tuff layers are intercalated in the middle to upper part, in which Shimamoto *et al.* (1998) recognized seven layers as keybeds (Kt-1 to Kt-7 tuff layers).

The geological age of the Kubota Formation has been determined by means of planktonic microfossils and radiometric dating of tuff layers (e.g. Aita, 1988; Takahashi and Amano, 1989; Taketani and Aita, 1991; Shimamoto *et al.*, 1998; Yanagisawa *et al.*, 2000; Takahashi *et al.*, 2001; Takahashi *et al.*, in press). Shimamoto *et al.* (1998) verified that the middle and upper parts of the Kubota Formation can be assigned to the calcareous nannofossil Zone CN6 to CN7/8a of Okada and Bukry (1980), planktonic foraminifer Zone N16 of Blow (1969) and the radiolarian *Lychnocanoma magnacornuta* Zone of Motoyama and Maruyama (1996). Yanagisawa *et al.* (2000) studied the diatom assemblages from the Kubota Formation for the first time and correlated the middle part with the diatom Zone NPD5C of Yanagisawa and Akiba (1998) (Figure 2).

On the other hand, Takahashi *et al.* (2001) dated the radiometric ages of a biotite-rich tuff layer, recognized as a keybed, the Kt-1 tuff layer, by Shimamoto *et al.* (1998). They reported the zircon fission-track age (F.T. age) and biotite potassium-argon age (K-Ar age) of the Kt-1 tuff layer to be 10.7±0.2 Ma (1 σ error) and 10.6±0.2 Ma (1 σ error). Moreover, Takahashi *et al.* (in press) dated the zircon fis-

Figure 3. Map showing the ostracode fossil localities (a part of 1:25,000 map of "Tanagura" and "Hanawa" published by Geographical Survey Institute of Japan).

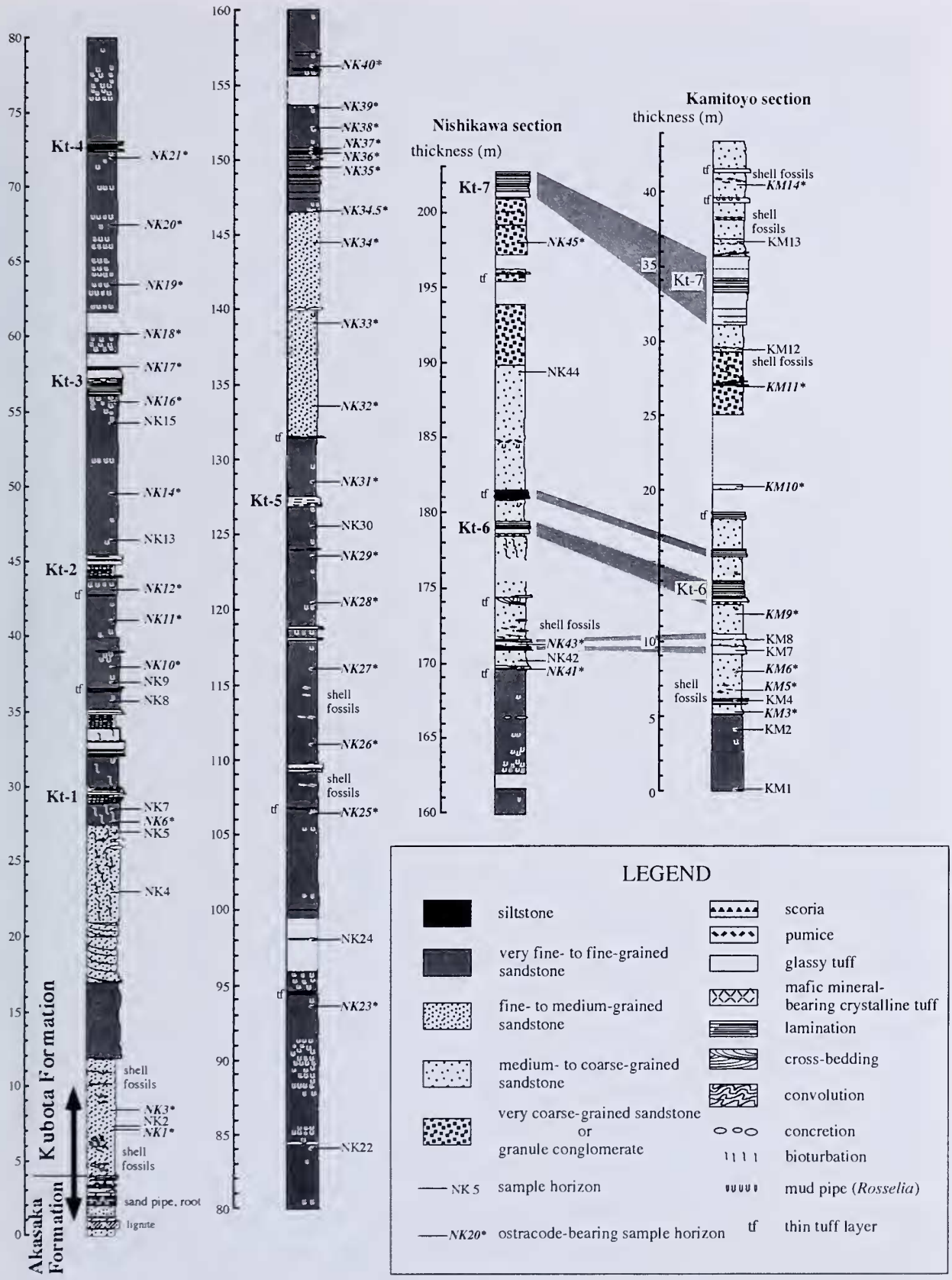


Figure 4. Columnar sections of the Kubota Formation. Bold italic numbers with asterisk marks indicate the ostracode samples in this study.

sion-track age of a felsic tuff, Kt-7, to be 10.6±0.3 Ma (1 σ error) (Figure 2). These reported microfossil and radiometric ages do not contradict the biochronology of Saito (1999).

Materials and methods

We collected 60 sediment samples from two sections of the Kubota Formation (Figures 3, 4) and examined 40 samples: 33 samples from the Nishikawa section and 7 samples from the Kamitoyo section. The Nishikawa section along the Nishikawa River is typical of the Kubota Formation (Shimamoto *et al.*, 1998). The upper part is better exposed in the Kamitoyo section along the Hokkawa River. We collected sediment samples from the Kamitoyo section to examine fossil ostracodes from the upper part of the Kubota Formation. These two sections are well correlated to each other by virtue of five keybeds.

Eighty grams of dried sediments were treated by using a saturated sodium sulfate solution and naphtha (Maiya and Inoue, 1973; Oda, 1978), washed through a 200 mesh sieve screen, and dried again. These procedures were repeated until the whole sediment sample became disintegrated. A fraction coarser than 125μm (115 mesh) was sieved and divided by a sample splitter into aliquot parts, from which 100 to 200 individuals were picked with a fine brush under the binocular microscope. We took micrographs with a JEOL Field Emission Scanning Electron Microscope, JSM-6330F to identify the taxonomic relationships of the fossil ostracodes (Figures 5, 6). The results of our identifications are listed in Figure 7. In this figure, the estimated preservation of ostracodes in each sample is as follows: good means the sample contained abundant specimens easily identified to species level; poor, the sample contained mostly specimens identified with difficulty to species level; moderate indicates somewhere between good and poor.

We examined ostracode assemblages in detail from those samples, each represented by more than fifty individuals by means of the proportions (relative abundance) of major species, species diversity and equitability and performed principal component analysis on data for abundance of major forty species.

Ostracode assemblages from the Kubota Formation

Ostracodes occurred in 36 samples and did not occur in 4 samples (samples NK1, 17, 18 and 45). We identified 67 ostracode taxa including those left in open nomenclature (Figure 7).

The ostracode assemblages from the Kubota Formation can be distinctly divided into two groups (Figure 8). In the lower part of the formation, *Spinileberis* sp. accounts for more than 90% of the assemblage. The genus *Spinileberis* has been reported to occur abundantly on muddy bottoms in Recent enclosed inner bays (e.g. Hanai, 1961; Ikeya and Shiozaki, 1993).

In the middle to upper part, *Schizocythere kishinouyei* (Kajiyama), *Kotoracythere abnorma* Ishizaki, *Hanaiborchella triangularis* (Hanai), *Cytheropteron miurense* Hanai, *Paracytheridea neolongicaudata* Ishizaki, *Finmarchinella japonica* (Ishizaki) and so on occurred. *S. kishinouyei* occurs most dominantly, forming 20 to 40% of the number of specimens in the assemblage. Subordinate are *K. abnorma* and *H. triangularis*, accounting for 10 to 20% of the number of specimens in the assemblage. Other species represent less than 10%. Most species are reported to live in coastal areas and the open sea under the influence of the Kuroshio Warm Current (e.g. Hanai, 1957, 1970; Ishizaki, 1981; Zhou, 1995; Tsukawaki *et al.*, 1997, 1998). All of these species are known to represent the Shiobara fauna (Ishizaki, 1966; Irizuki and Matsubara, 1994, 1995; Ishizaki *et al.*, 1996; Irizuki *et al.*, 1998). Through the upper horizons of the middle part to the upper part, the relative abundance of *Kotoracythere abnorma* increases (Figure 8).

Faunal structures

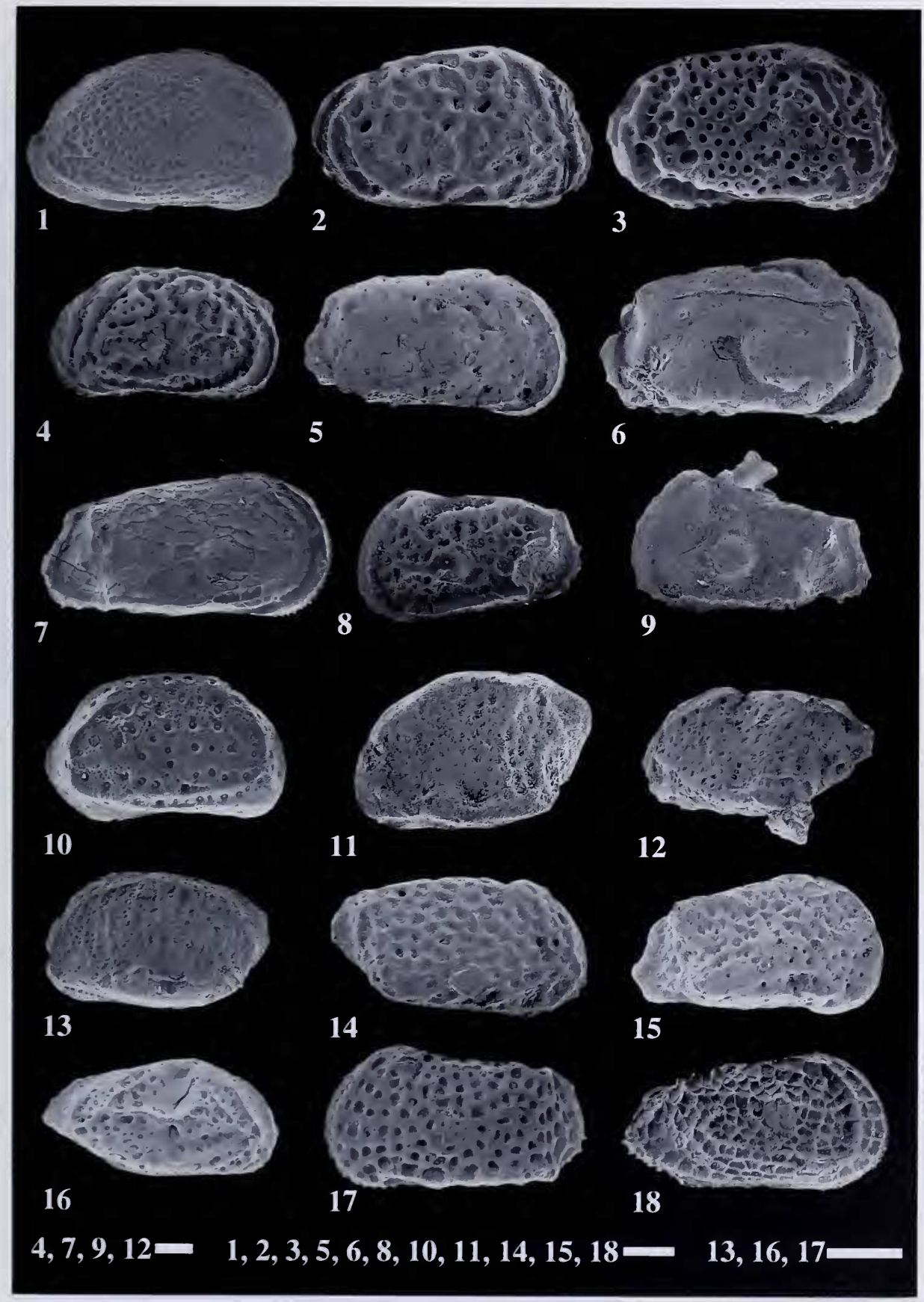
The faunal structures of ostracode assemblages were expressed by the following four indices: species diversity [$H(S)$], equitability ($Eq.$), the number of species, and number of individuals per 10 g sediment sample. These indices have been used extensively in paleoecology. Figure 9 shows vertical changes of these indices. Changes in faunal structures may be related to environmental changes (e.g., Buzas and Hayek, 1998). Species diversity [$H(S)$] and equitability ($Eq.$) are expressed by the Shannon-Wiener formula and the equation of Buzas and Gibson (1969), respectively:

$$H(S) = -\Sigma p_i \ln p_i \text{ and } Eq. = \exp[H(S)]/S$$

where p_i means the proportion (relative abundance) of the i-th species in a sample and S the number of species.

In the middle part of the Kubota Formation, the values of $H(S)$ and $Eq.$ range from 2.08 to 3.00 and from 0.44 to 0.64, respectively. The number of species in each sample varies from 20 to 40. Vertical changes of $Eq.$ values are little. $H(S)$ values and the number of species change synchronously. Through the upper horizon of the middle to upper part (samples NK41 and KM3) , $H(S)$ values and the number

➡ **Figure 5.** Scanning electron micrographs of selected ostracode species from the Kubota Formation. All specimens, expect for one juvenile one (7), represent adult valves. All scale bars indicate 100 μm. RV = right valve; LV = left valve. **1:** *Aurila* sp., RV, loc. NK27. **2:** *Callistocythere hatatatensis* Ishizaki, RV, loc. NK34.5. **3:** *Callistocythere kotorai* Ishizaki, RV, loc. NK35. **4:** *Callistocythere* sp.2, LV, loc. NK36. **5:** *Coquimba* cf. *ishizakii* Yajima, RV, loc. NK25. **6:** *Coquimba* sp.1, RV, loc. NK10. **7:** *Coquimba* sp.2, RV, loc. NK27. **8:** *Cornucoquimba saitoi* (Ishizaki), LV, loc. NK35. **9:** *Cornucoquimba moniwensis* (Ishizaki), LV, loc. NK21. **10:** *Cythere omotenipponica* Hanai, RV, loc. NK27. **11:** *Cytheropteron miurense* Hanai, LV, loc. KM3. **12:** *Cytheropteron* cf. *sawanense* Hanai, LV, loc. NK10. **13:** *Cytheropteron subuchioi* Zhao, LV, loc. NK27. **14:** *Eucytherura neoalae* Ishizaki, RV, loc. NK21. **15:** *Finmarchinella japonica* (Ishizaki), RV, loc. NK27. **16:** *Hanaiborchella triangularis* (Hanai), RV, loc. NK27. **17:** *Yezocythere gorokuensis* (Ishizaki), LV, loc. NK27. **18:** *Trachyleberis* sp., RC, loc. NK35.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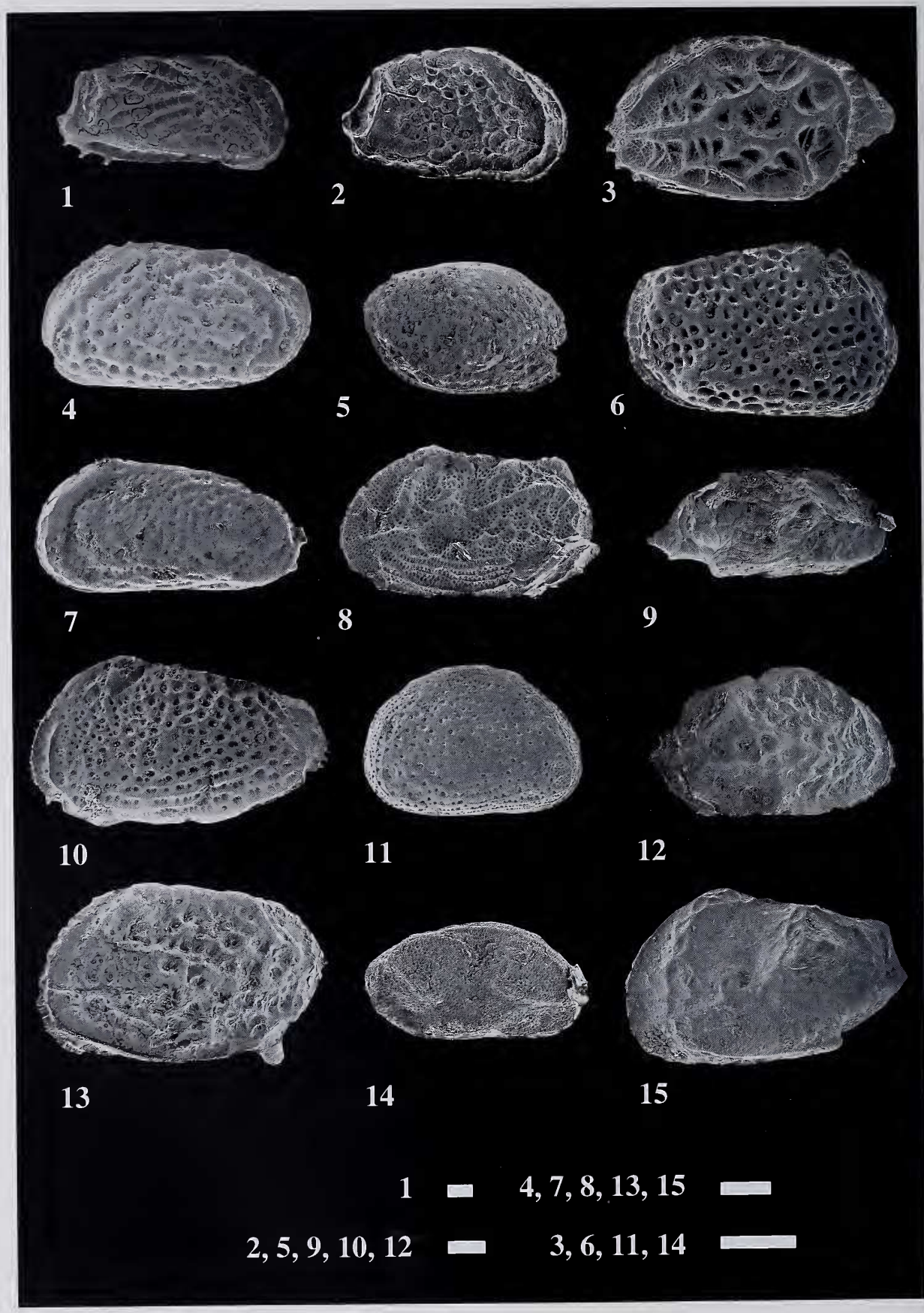
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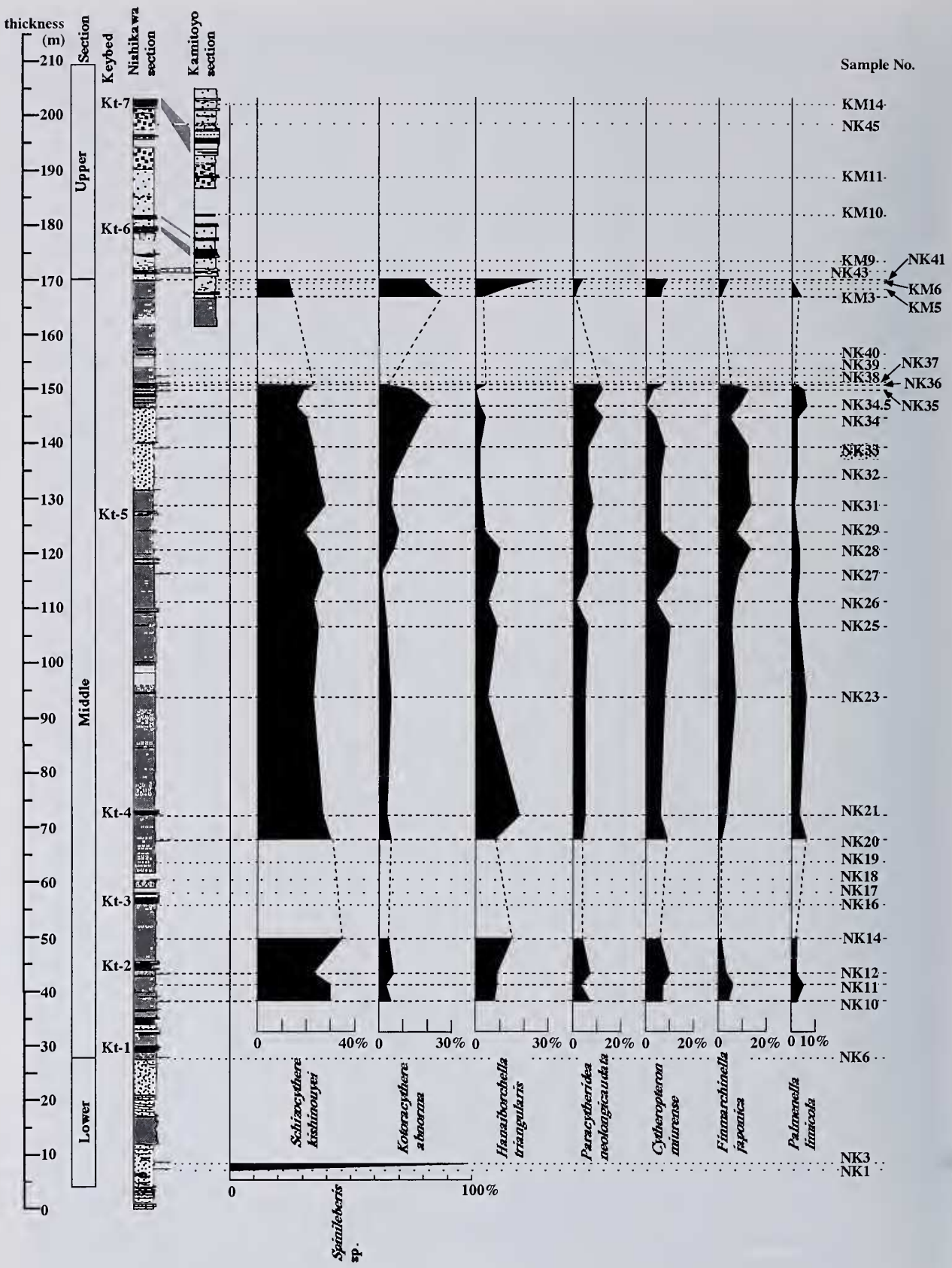
species/sample	NK3	NK6	NK10*	NK11*	NK12*	NK14*	NK16	NK19	NK20*	NK21*	NK23*	NK25*	NK26*	NK27*	NK28*	NK29*	NK31*	NK32*	NK33*	NK34*	NK34.5*	NK35*	NK36*	NK37	NK38	NK39	NK40	NK41*	NK43	KM3*	KM5	KM6	KM9	KM10	KM11	KM14
Acanthocythereis spp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Aurila cymba (Brady)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
• *Aurila* sp.	0	0	5	1	0	0	0	0	0	0	0	2	2	11	5	7	12	5	6	4	4	10	6	0	0	0	0	0	0	0	0	0	0	0	0	0
• *Aurila* spp.	1	0	0	0	0	0	0	0	1	1	2	0	0	0	0	0	2	0	0	3	3	0	3	0	0	0	0	0	2	1	0	0	0	0	0	0
Callistocythere kotorui Ishizaki	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	1	0	0	0	1	0	0	1	0	0	0	0	0	0
• *Callistocythere hatatatensis* Ishizaki	0	0	1	1	0	0	0	0	0	0	1	1	0	0	2	0	2	0	3	14	4	11	8	0	0	0	0	1	0	0	0	0	0	0	0	0
• *Callistocythere rugosoforma* Ishizaki	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	3	0	0	0	1	0	0	0	0	0	0	0	0	0
• *Callistocythere subsetunensis* Ishizaki	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Callistocythere undulatifacialis Hanai	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Callistocythere sp.1	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
• *Callistocythere* sp.2	0	0	3	1	0	0	0	0	0	0	0	2	0	3	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Callistocythere spp.	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
• *Coquimba* cf. *ishizakii* Yajima	0	0	0	0	1	0	0	0	0	0	0	1	4	2	0	0	0	0	3	5	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0
• *Coquimba* sp.1	0	0	1	2	0	0	0	0	0	1	4	5	12	3	0	14	14	12	10	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Coquimba sp.2	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Coquimba spp.	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
• *Coquimba* ? spp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	4	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
• *Cornucoquimba moniwensis* (Ishizaki)	0	0	5	7	8	5	0	0	5	4	12	0	4	4	2	8	7	2	10	1	0	3	5	0	0	0	0	0	1	0	1	0	0	0	0	1
• *Cornucoquimba saitoi* (Ishizaki) s.l.	0	0	8	9	2	1	0	0	6	7	14	16	4	13	14	6	5	4	0	7	19	9	7	0	0	0	0	1	4	14	9	1	0	5	0	2
• *Cornucoquimba* spp.	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0
• *Cythere omotenipponica* Hanai	0	0	0	7	1	0	0	0	0	0	2	2	2	3	3	1	2	2	1	1	5	4	12	0	0	0	1	0	1	3	2	0	0	0	0	1
• *Cythere* spp.	0	0	1	6	1	0	0	0	6	4	14	1	9	10	4	3	6	4	6	2	8	9	0	2	1	0	0	3	0	0	1	1	0	0	0	0
Cythere ? spp.	0	0	0	1	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
• *Cytheropteron miurense* Hanai	0	0	11	12	10	6	0	0	10	8	18	17	6	28	24	11	15	10	18	9	1	6	14	0	0	0	0	7	0	5	2	0	0	0	0	2
• *Cytheropteron sawanense* Hanai	0	0	2	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Cytheropteron cf. *sawanense* Hanai	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cytheropteron subuchioi Zhao	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
• *Cytheropteron uchioi* Hanai	0	0	1	3	3	0	0	0	3	2	6	1	0	1	0	1	0	3	4	0	1	2	4	0	0	0	0	0	2	0	0	0	0	0	0	0
Cytheropteron sp.1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cytheropteron spp.	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
• *Eucytherura neoalae* Ishizaki	0	0	4	4	3	1	0	0	0	3	2	1	2	0	0	3	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
• *Finmarchinella japonica* (Ishizaki) s.l.	0	0	7	10	3	1	0	0	1	4	16	8	10	19	22	14	33	22	26	9	17	24	7	0	0	0	7	3	0	1	0	0	0	1	0	0
Finmarchinella sp.	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Finmarchinella spp.	0	0	1	0	0	0	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
• *Finmarchinella* ? spp.	0	0	0	0	3	0	0	0	0	2	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
• *Hanaiborchella triangularis* (Hanai)	0	1	13	16	9	14	1	2	8	23	11	15	8	22	17	7	7	4	5	8	5	1	7	2	2	1	2	20	1	3	0	0	0	0	0	1
• *Hemicythere kitanipponica* Tabuki	0	0	2	3	0	0	0	0	1	0	3	0	10	0	0	4	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hemicythere spp.	0	0	0	1	0	0	0	0	2	0	1	1	1	1	0	2	1	0	0	2	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0
Hemicytherura clathrata (Sars)	0	0	0	0	0	0	0	0	0	1	0	0	0	2	0	1	1	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0
• *Hemicytherura cuneata* Hanai	0	0	0	1	0	0	0	0	0	0	0	0	1	0	3	2	1	1	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0
• *Hemicytherura kajiyamai* Hanai	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	1	1	4	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1
Hemicytherura yamaguchii (Tabuki)	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
• *Hermanites posterocostatus* Ishizaki	0	0	2	3	1	0	0	0	0	0	1	1	3	2	0	2	3	2	5	0	1	4	2	0	0	0	0	0	0	1	0	0	0	0	0	0
• *Kotoracythere abnorma* Ishizaki	0	5	9	5	6	4	0	0	5	4	12	8	4	3	10	16	12	10	27	37	42	27	4	1	0	1	2	14	4	23	13	1	1	2	1	4
• *Kotoracythere* spp.	0	0	0	0	0	0	0	0	0	0	6	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
• *Loxoconcha nozokiensis* Ishizaki	0	0	0	1	0	0	0	0	0	0	1	0	3	1	4	8	4	5	17	10	7	0	7	0	0	0	0	0	0	3	1	0	0	0	0	0
• *Loxoconcha* spp.	0	0	0	0	9	7	0	0	0	1	0	0	0	0	0	0	7	0	0	0	1	0	1	0	0	0	1	0	0	3	0	0	0	0	0	0
• *Loxocorniculum* sp.	0	0	3	6	0	0	1	0	6	0	3	0	4	0	0	11	1	4	4	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Metacytheropteron sp.	0	0	0	0	1	1	0	0	1	0	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
• *Munseyella hatatatensis* Ishizaki	0	0	1	0	0	0	0	0	0	0	0	2	0	1	0	1	0	0	0	0	2	0	3	0	0	0	0	0	1	0	0	0	0	0	0	0
Munseyella spp.	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	2	1	0	0	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0
Neonesidea sp.	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
• *Palmenella limicola* (Norman)	0	1	3	9	2	2	0	0	6	4	14	5	3	6	6	3	3	4	4	4	12	10	2	0	0	0	0	0	0	4	0	0	0	0	0	0
• *Paracytherídea neolongicaudata* Ishizaki	0	0	12	5	7	4	0	1	5	6	14	9	1	14	8	11	22	10	11	26	17	25	22	2	0	0	3	3	1	1	1	0	0	0	0	1
Pontocythere sp.	0	0	0	0	1	0	0	0	0	0	0	0	0	0	2	0	1	2	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
• *Robertsonites* sp.	0	0	0	0	0	0	0	0	0	3	0	2	0	0	0	1	0	1	0	1	2	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
• *Rotundracythere* ? sp.	0	0	12	5	1	9	4	6	6	11	3	11	7	7	0	2	4	2	0	0	0	0	0	3	0	0	1	5	0	0	0	0	0	0	0	0
• *Schizocythere hatatatensis* Ishizaki	0	0	1	0	0	1	0	0	0	0	0	1	1	2	1	3	1	1	3	5	2	3	4	0	0	0	0	0	0	6	2	0	0	0	0	1
Schizocythere cf. *hatatatensis* Ishizaki	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
• *Schizocythere kishinouyei* (Kajiyama)	0	1	50	55	23	33	2	0	32	34	54	42	37	64	42	38	78	48	51	45	39	40	48	0	0	0	7	10	4	17	10	0	0	1	1	4
Schizocythere spp.	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	2	0	2	0	0	0
• *Semicytherura henryhowei* Hanai and Ikeya	0	0	7	6	4	5	0	0	1	2	5	3	7	3	2	2	3	2	0	1	0	2	1	0	0	0	0	1	0	0	0	0	0	0	0	0
Spinileberis sp.	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
• *Trachyleberis* sp.	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	3	1	0	1	0	0	1	2	0	0	0	0	0	0	0	0	0	0	2	0	0
Trachyleberis spp.	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
• *Yezocythere goroluensis* (Ishizaki)	0	0	0	0	1	0	0	0	0	2	0	1	5	1	2	6	6	6	7	2	4	4	3	0	0	0	0	6	0	0	0	0	0	0	0	0
Yezocythere spp.	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total specimens	22	8	169	181	101	95	8	9	105	127	229	163	164	234	176	200	259	182	223	200	209	203	195	10	3	2	30	76	25	87	46	3	3	12	3	19
Preservation	G	M	G	G	G	M	M	M	M	G	M	G	G	G	M	G	G	M	G	G	M	M	G	M	P	M	G	M	G	G	G	P	P	G	M	G

Figure 7. List of ostracode species from the Kubota Formation. Asterisk marks indicate samples and species used for with principal component analysis. Abbreviation for preservation: G = good, M = moderate and P = poor.

← **Figure 6.** Scanning electron micrographs of selected ostracode species from the Kubota Formation. All are adult specimens. All scale bars indicate 100 µm. RC = right lateral view of carapace. **1:** *Hermanites posterocostatus* Ishizaki, RV, loc. NK27. **2:** *Hemicythere kitanipponica* (Tabuki), RV, loc. NK34.5. **3:** *Hemicytherura cuneata* Hanai, LV, loc. NK27. **4:** *Kotoracythere abnorma* Ishizaki, LV, loc.NK35. **5:** *Loxoconcha nozokiensis* Ishizaki, RV, loc. NK36. **6:** *Loxocorniculum* sp., LV, loc. NK27. **7:** *Munseyella hatatatensis* Ishizaki, LV, loc. NK40. **8:** *Palmenella limicola* (Norman), LV, loc. NK21. **9:** *Paracytherídea neolongicaudata* Ishizaki, RV, loc. NK34. **10:** *Robertsonites* sp., LV, loc. NK35. **11:** *Rotundracythere* ? sp., RV, loc. NK27. **12:** *Schizocythere kishinouyei* (Kajiyama), RV, loc. KM3. **13:** *Schizocythere hatatatensis* Ishizaki, LV, loc. KM3. **14:** *Semicytherura henryhowei* Hanai and Ikeya, RV, loc. NK21. **15:** *Spinileberis* sp., LV, loc. NK3.


thickness (m)
Section
Keybed
Nishikawa section
Kamitoyo section
Sample No.
Upper
Middle
Lower
Kt-7
Kt-6
Kt-5
Kt-4
Kt-3
Kt-2
Kt-1
KM14
NK45
KM11
KM10
KM9
NK43
KM3
NK41
KM6
KM5
NK40
NK39
NK38
NK37
NK36
NK34.5
NK35
NK34
NK33
NK32
NK31
NK29
NK28
NK27
NK26
NK25
NK23
NK21
NK20
NK19
NK18
NK17
NK16
NK14
NK12
NK11
NK10
NK6
NK3
NK1
0 40%
0 30%
0 30%
0 20%
0 20%
0 20%
0 10%
Schizocythere kishinouyei
Koloracythere abnorma
Hanaiborchella triangularis
Paracytheridea neolongicaudata
Cytheropteron miurense
Finmarchinella japonica
Palmenella limicola
0 100%
Spinileberis sp.

of species decrease.

The number of individuals in sample NK3 is 0.2 per 10 g sediment. Samples from the middle and upper parts contain about 40 to 400 and less than about 10 individuals per 10g, respectively.

Principal component analysis

In order to elucidate bottom environments of the Kubota Formation, 21 samples which contained more than 50 individuals and 40 species represented by more than three individuals at least in a sample were subjected to Q-mode principal component analysis. The analysis was carried out to obtain clues to the intersample relationship and to identify end members (samples having extreme properties). However, the correlation coefficient may be considered inappropriate as a measure of similarity between samples because it requires calculation of variance across variables (Davis, 1986). Therefore, the analysis in this study was based on the covariance matrix. The computer program used in this study was a modified version written by Furuya and Obata (1996). The results of the analysis show that the first two components account for about 85 % of the total variation, which should be sufficient for discussion of general distribution patterns of the ostracode assemblages (Table 1). Figure 10 shows the stratigraphic distribution of eigenvectors in relation to the first two components.

The first component

This component explains more than 77% of the total variation. *Schizocythere kishinouyei* (score = +113.9), *Kotoracythere abnorma* (score = +35.9), *Hanaiborchella triangularis* (score = +34.5) and *Cytheropteron miurense* (score = +32.6) contribute greatly to this component. They are abundant in most of the samples examined. Recent representatives of these species are mostly known to occur predominantly in littoral to sublittoral habitats, which are influenced by the Kuroshio Warm Current (e.g. Hanai, 1957, 1970; Ishizaki, 1966, 1981; Zhou, 1995; Tsukawaki *et al.*, 1997, 1998). The first component is interpreted to represent the abundance of ostracode species.

The second component

This component explains more than 7% of the total variation. *Kotoracythere abnorma* (score = +32.0) and *Cornucoquimba saitoi* s.l. (score = +8.8) have high positive scores of the second component. *Hanaiborchella triangularis* (score = −8.1), *Rotundracythere*? sp. (score = −7.9) and *Schizocythere kishinouyei* (score = −7.1) have high negative scores of the second component. *K. abnorma* and *C. saitoi* are extinct species. *K. abnorma* occurs in the middle Miocene Hatatate Formation, but does not occur in the Moniwa Formation, which is overlain conformably by the Hatatate Formation (Ishizaki, 1966). Kitamura *et al.* (1986) suggested that the Hatatate and Moniwa Formations were deposited in lower sublittoral to bathyal and upper sublittoral settings, respectively, based on sedimentary facies and benthic foraminifer assemblages. Hence, *K. abnorma* is considered as having lived in the lower sublittoral zone under the influence of open sea water. Because *C. saitoi* also occurs in the Hatatate Formation, it is regarded as having lived under the influence of open sea water (Ishizaki, 1966). Thus, species having high positive scores are considered as having lived in the open sea. On the other hand, species having high negative scores are reported from Recent seas, except for *Rotundracythere*? sp. *H. triangularis* is reported from the mouth of Ise and Mikawa Bays (Bodergat and Ikeya, 1988). *Rotundracythere*? sp. occurs in the Pleistocene Sasaoka Formation (Ishizaki and Matoba, 1985). Because *Rotundracythere*? sp. occurs with shallow marine molluscs, it is regarded as having likewise lived in shallow marine waters. *S. kishinouyei* is reported from an upper sublittoral zone under the influence of coastal currents in the eastern China sea (Ishizaki, 1981). Therefore, species having high negative scores are considered as having lived in shallow seas influenced by coastal currents. Consequently, the second component is interpreted as signalling changes of water mass: positive and negative eigenvectors represent the stronger and weaker influence of open sea water, respectively.

Discussion

Water depths

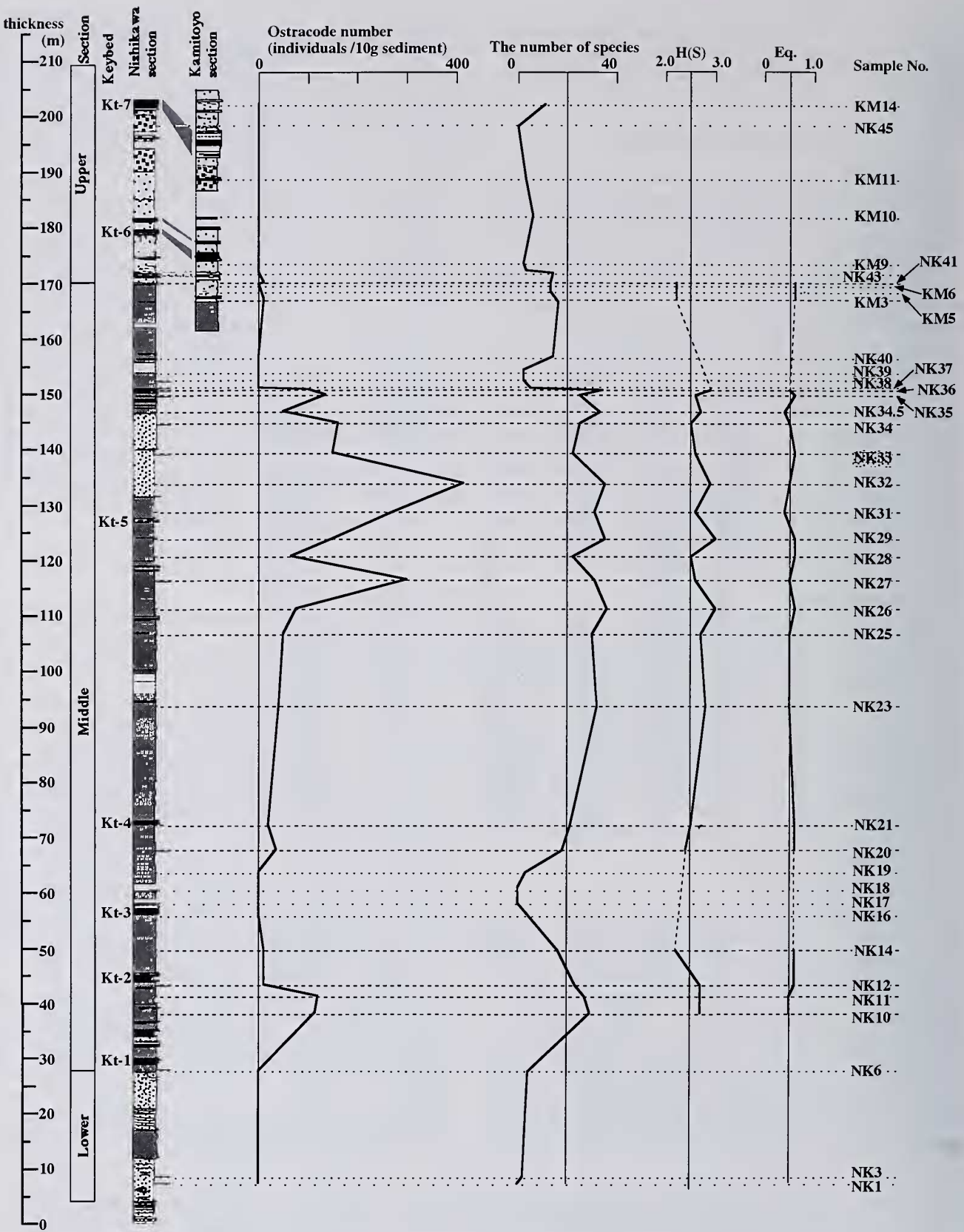
In the lower part of the Kubota Formation, *Spinileberis* sp. occurs dominantly. This fact suggests that the lower part was a deposit in an enclosed inner bay (e.g. Ikeya and Shiozaki, 1993).

Most of the ostracode species from the middle part of the formation are reported in Recent shallow seas, as mentioned above. Moreover, the faunal structures of the ostracode assemblages from the unit indicate high values of *H*(*S*), *Eq.* and the number of species. For example, the faunal structures of ostracode assemblages in the outer part of Uranouchi Bay show values of *H*(*S*), *Eq.* and the number of species that are 2.0 to 3.0, 0.4 to 0.6 and 20 to 40, respectively (Ishizaki, 1979). These values approximate those of the middle part. Thus, the ostracode assemblage from the middle part of the Kubota Formation represents a sublittoral setting. Vertical changes of the second component eigenvectors indicate that the influence of open sea water became stronger in the upward sequence.

In the upper part, the low occurrence of ostracodes means that paleodepths cannot be assessed, except for the horizon of the sample KM3. The sample KM3 has a positive second-component eigenvector and the horizon of the sample was deposited under the influence of open sea water.

As already mentioned, Iwasaki (1970) studied the molluscan fauna from the Kubota Formation. He reported

← **Figure 8.** Diagram showing the vertical changes for the relative abundance of major species. Broken lines show samples containing more than 50 individuals of ostracodes. Dotted lines represent samples containing less than 50 individuals. Loose dotted lines represent samples containing no ostracode. For explanation of columnar sections see the legend of Figure 4.


thickness (m)
Section
Keybed
Nishikawa section
Kamitoyo section
Ostracode number (individuals /10g sediment)
0
400
The number of species
0
40
2.0 H(S) 3.0
0 Eq. 1.0
Sample No.
Upper
Middle
Lower
Kt-7
Kt-6
Kt-5
Kt-4
Kt-3
Kt-2
Kt-1
KM14
NK45
KM11
KM10
KM9
NK43
KM3
NK41
KM6
KM5
NK40
NK39
NK38
NK37
NK36
NK34.5
NK35
NK34
NK33
NK32
NK31
NK29
NK28
NK27
NK26
NK25
NK23
NK21
NK20
NK19
NK18
NK17
NK16
NK14
NK12
NK11
NK10
NK6
NK3
NK1

the *Ostrea* and *Anadara-Dosinia* assemblages from the lower part, the *Lucinoma-Turritella* assemblage from the middle part and the *Mizuhopecten-Chlamys* assemblage from the upper part. These molluscan assemblages represent the following habitat conditions, referring to the paleobathymetric indices of molluscan fossils shown by Ogasawara and Masuda (1989): 1) the lower part represents an inner-bay environment with water depths shallower than 30 m; 2) the middle part represents depths between 100 and 200m; 3) the upper part represents depths of 30 m or less under the influence of the open sea. These estimates based on molluscan fossils from the Kubota Formation are generally consistent with the water depths suggested by ostracodes.

Shimamoto *et al.* (1998) examined foraminifer, radiolarian and molluscan fossils and showed the successive changes of the planktonic/benthic foraminifer ratio (P/B ratio). They thought that the lower part was deposited in an inner bay because of the occurrence of *Ostrea* of *in-situ* origin, while the middle part was in an open sea shallower than about 100 m based on P/B ratios. Consequently, they concluded that the Kubota Formation represents a sequence of marine transgression and regression. Vertical changes of water depths suggested by ostracodes are largely consistent with their views. On the other hand, decreasing frequency of radiolarians in the upward sequence of the middle part suggests that influence of the open sea water became feeble. This representation contradicts one based on vertical changes of second-component eigenvectors. Some workers have pointed out that radiolarian assemblages from the Kubota Formation contain many reworked individuals (Taketani and Aita, 1991; Shimamoto *et al.*, 1998). Therefore, the reported frequency of radiolarians is regarded as not sufficiently representing paleoenvironmental settings during deposition of the middle part. Consequently, the middle part was subject to the strong influence of open sea water in its upward sequence.

Marine climates

In the lower part of the Kubota Formation, the only dominant species is *Spinileberis* sp. Recent species of this genus are widely distributed from southern China to northern Japan and occur abundantly in bays influenced by warm coastal waters (e.g. Hanai, 1961; Ishizaki, 1971; Ikeya and Shiozaki, 1993). Hence, the lower part is considered to have been deposited under the influence of warm coastal waters.

In the middle part, Recent representatives of *Schizocythere kishinouyei*, *Hanaiborchella triangularis* and *Cytheropteron miurense* among the dominant species are reported from shallow seas under the influence of the Kuroshio Warm Current (e.g. Ishizaki, 1981; Zhou, 1995). However, such circumpolar and cryophilic species as *Hemicytherura clathrata*, *Munseyella hatatatensis*, *Palmenella limicola*, *Finmarchinella japonica* s.l. and *Hemicythere kitanipponica* also occurred sparsely (Figure 10). Circumpolar and cryophilic species are members of high-latitude genera (Cronin and Ikeya, 1987). Irizuki and Matsubara (1995) and Irizuki *et al.* (1998) also reported that circumpolar and cryophilic species occurred with warm-water species in the Miocene deposits. They considered that the Miocene circumpolar and cryophilic species may not have experienced such subfrigid to frigid environments as their Recent counterparts and lived in slightly colder conditions than the other species because of the absence of fossil records for them from the mid-Neogene climatic optimum horizon of southwestern Japan (Ishizaki, 1963; Yajima, 1988, 1992). Hence, the middle part of the formation was deposited in a warm shallow sea under the feeble influence of cooler currents.

Ostracodes are sparse in the upper part of the formation. However, species forming assemblages do not show any distinct change, comparing with the assemblages from the middle part. Hence, the upper part may also have been deposited in warm-water conditions.

As mentioned above, Ogasawara (1994) studied the relations between marine climates and Neogene molluscan faunas, considering their tolerance for marine climates. Moreover, he divided the Shiobara fauna into older and younger faunas based on characteristic species of each fauna. The molluscan fauna from the Kubota Formation belongs to the younger Shiobara fauna, because *Mizuhopecten paraplebejus* and *Kaneharaia kaneharai*, both of which characterize the younger fauna, were reported (Iwasaki, 1970). Ogasawara (1994) mentioned that the younger Shiobara fauna had lived in the warm- to mild-temperate realms of Nishimura's (1981) zoogeographical classification of modern marine faunas around the Japanese Islands.

Marine paleoclimates represented by ostracode fauna from the Kubota Formation strongly supported Ogasawara's (1994) views.

Conclusions

1) Sixty-seven ostracode species including those left in open nomenclature were reported for the first time from the upper Miocene Kubota Formation. The fauna is characterized by the abundance of warm-water species.

2) The ostracode fauna from the Kubota Formation reveals an enclosed inner bay paleoenvironment influenced by warm water for the lower part and a warm shallow sea under the feeble influence of cold water for the middle to upper part. Hence, the Shiobara fauna from the Kubota Formation flourished in a warm shallow sea.

3) Results of principal component analysis of successively collected ostracode samples suggest that the middle part of the Kubota Formation was strongly influenced by

← **Figure 9.** Diagram showing the vertical changes of the ostracode abundance of individuals per 10g sediment, number of species, species diversity (*H*(*S*)) and equitability (*Eq.*). Broken lines show samples containing more than 50 individuals of ostracodes. Dotted lines represent samples containing less than 50 individuals. Loose dotted lines represent samples containing no ostracode. For explanation of columnar sections see the legend of Figure 4.

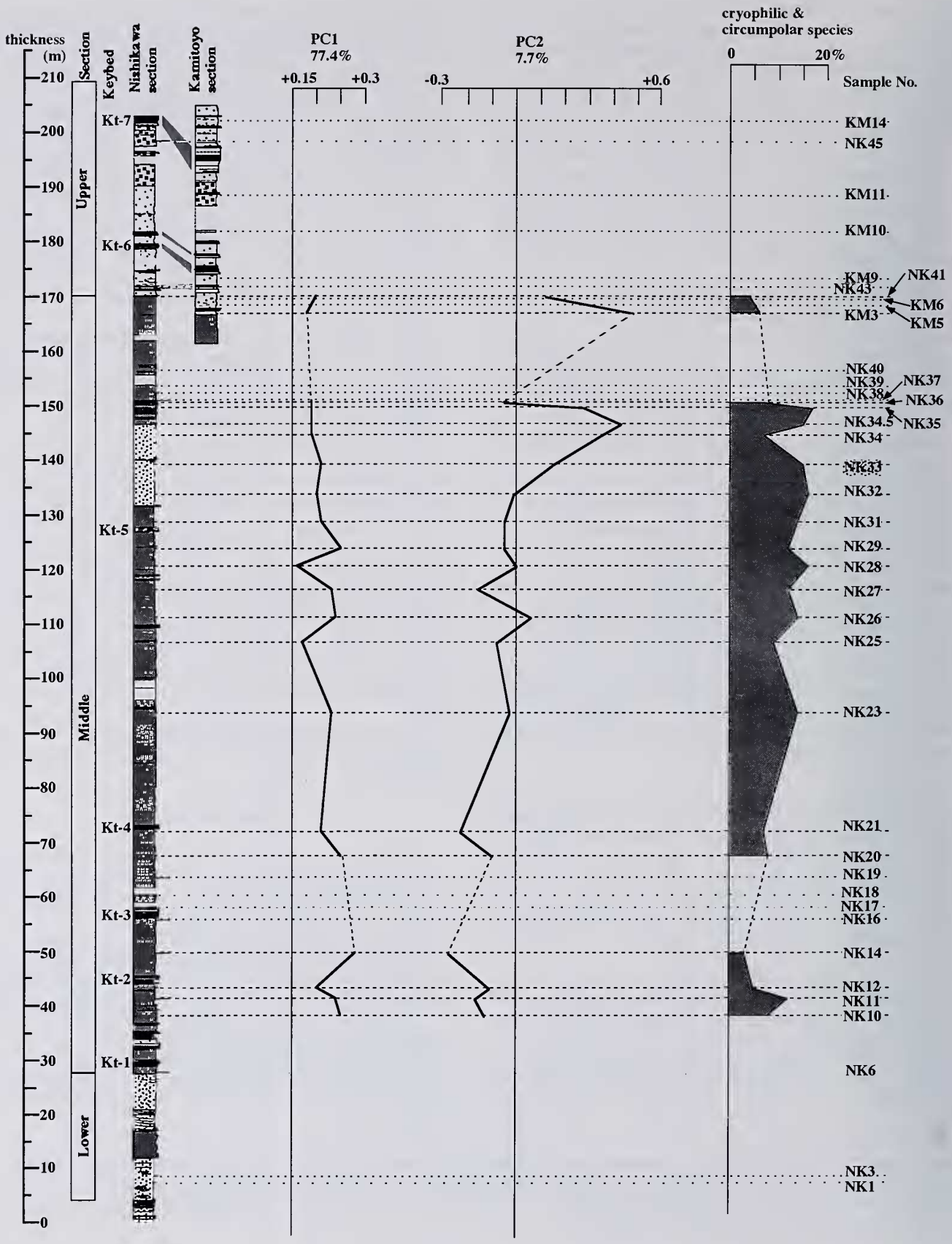

thickness (m)
Section
Keybed
Nishikawa section
Kamitoyo section
PC1 77.4%
+0.15
+0.3
PC2 7.7%
-0.3
+0.6
cryophilic & circumpolar species
0
20%
Sample No.
Upper
Middle
Lower
Kt-7
Kt-6
Kt-5
Kt-4
Kt-3
Kt-2
Kt-1
KM14
NK45
KM11
KM10
KM9
NK43
KM3
NK41
KM6
KM5
NK40
NK39
NK38
NK37
NK36
NK34.5
NK35
NK34
NK33
NK32
NK31
NK29
NK28
NK27
NK26
NK25
NK23
NK21
NK20
NK19
NK18
NK17
NK16
NK14
NK12
NK11
NK10
NK6
NK3
NK1

Table 1. Summary of principal component analysis.

	Eigenvalue	Percentage	Cumulative Percentage
PC 1	380.5	77.4	77.4
PC 2	37.8	7.7	85.1

open sea water in its upward sequence.

Acknowledgments

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← **Figure 10.** Diagram showing vertical changes of eigenvectors with respect to the first two components and the proportion of cryophilic and circumpolar ostracode species. Broken lines show samples containing more than 50 individuals of ostracodes. Dotted lines represent samples containing less than 50 individuals. Loose dotted lines represent samples containing no ostracode. For explanation of columnar sections see the legend of Figure 4.

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